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SEMIAUTOMATIC APPARATUS FOR CREEP AND STRESS-RUPTURE TESTS OF THIN-WALL FUEL-CLADDING TUBES UNDER INTERNAL GAS-PRESSURE LOADING

F. L. Yaggee, J. W. Styles, and S. B. Brak

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by

F. L. Yaggee, J. W. Styles, and S. B. Brak*

Materials Science Division

September 1971

*Central Shops Department

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SEMIAUTOMATIC APPARATUS FOR CREEP AND STRESS-RUPTURE TESTS OF THIN-WALL FUEL-CLADDING TUBES UNDER INTERNAL GAS-PRESSURE LOADING

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ABSTRACT

A semiautomatic apparatus is described for creep and stress-rupture tests of small-diameter, thin-wall tubes under biaxial load. Twenty-four specimens, arranged in four bundles each with six specimens, are accommodated in a single test. Each bundle is connected to a common source of high-pressure gas. Creep or stress-rupture tests can be conducted under constant-load (constant-pressure) or constant-stress (decreasing-pressure) conditions at temperatures to 1200°C in a vacuum or an inert-gas environment.

Biaxial creep tests were conducted on Types 304 and 304L stainless steel tubes at temperatures between 550 and 700°C and applied tangential stresses between 7500 and 40,000 psi. Test results have yielded a value of 6.7 for the stress dependence of the steady-state creep rate and 95,000 cal/mole for the activation energy of creep. Both values are in good agreement with the published values for 18-8 austenitic stainless steel determined in uniaxial creep tests. Experimental results provide a strain profile of the three types of specimen failures normally observed: catastrophic rupture, pinhole leak, and fissure. The results also yield information on the change in material density as a function of diametral strain, strain rate, and temperature.

I. INTRODUCTION

The creep of small-diameter, thin-wall tubes under biaxial stress is relevant to the creep of reactor fuel cladding. Biaxial creep data are therefore important to fuel-element design.

Fuel-element cladding stressed by internal gas pressure or fuel swelling can fail in either of two modes: by a pinhole perforation of the tube wall, or by violent rupture of the tube wall. The loss of internal pressure is gradual in a pinhole-leak failure, but is sudden in rupture failure. In either case, the cladding failure differs markedly from the parting failures usually associated with sheet or rod specimens tested under uniaxial tension. The difference in the constraints imposed on the specimen in biaxial and uniaxial tests and the difference in the definition of failure in the two types of tests lead to a variation in the values obtained for failure strength, time to failure, uniform strain, and strain at failure for the same material tested under similar conditions. Biaxial creep or stress-rupture tests are generally used to obtain mechanical-property data on tubing when the intended application is in the form of tubing.[1-6] If the same tubing is used in the unirradiated and in-reactor biaxial creep tests,[7] data from the former can be used as a base of reference to evaluate the effects of irradiation on creep properties. This approach is advantageous because it eliminates the usual concerns about differences in thermomechanical history, grain size, and texture of the material used in the two tests.

The apparatus to be described was designed to provide biaxial creep and stress-rupture data for small-diameter, thin-wall, fuel-cladding materials under stress and temperature conditions approximating those of the actual application. The pressure integrity of this equipment is comparable to an unfailed fuel element. The pressure integrity makes possible the detection of subtle changes in creep behavior and failure mode that may occur in an actual fuel element. Twenty-four specimens in four bundles, each with six specimens, can be accommodated at one time. Because each specimen bundle can be pressurized independently, a single test can yield biaxial creep data at a common temperature and four pressures that correspond to four tangential stresses.

Two units of this apparatus (Biaxial Creep Tester--Mark II) have been constructed and are currently in operation. One unit is being used at ANL-Illinois in biaxial creep, stress-rupture, and fracture studies of unirradiated cladding materials. The second unit is being used in the Fuels and Examination Facility at EBR-II (ANL-Idaho) for postirradiation surveillance testing of driver-fuel cladding as well as other cladding used in fueled and unfueled in-reactor experiments. This latter unit extends the short-term, tube-burst tests, formerly the standard for evaluating postirradiation cladding behavior, into the creep regime.[3] The reliability of the design was proven with an earlier model of this apparatus.[8]

II. EQUIPMENT DESCRIPTION

The apparatus consists of a high-pressure gas system, a heated vacuum furnace chamber, associated vacuum pumping equipment, and electronic devices for pressure, temperature, and vacuum control. Specimen pressure and temperature, furnace temperature and vacuum, and the duration of the test are continuously monitored to failure on recording- and digital-indicating instrumentation. Tests can be conducted in either a vacuum or an inert-gas environment in an automatic or manual operating mode. In the automatic operating mode, the electronic controls for pressure, temperature, and vacuum interact in a prescribed sequence following each specimen failure. A general view of the apparatus is shown in Fig. 1.

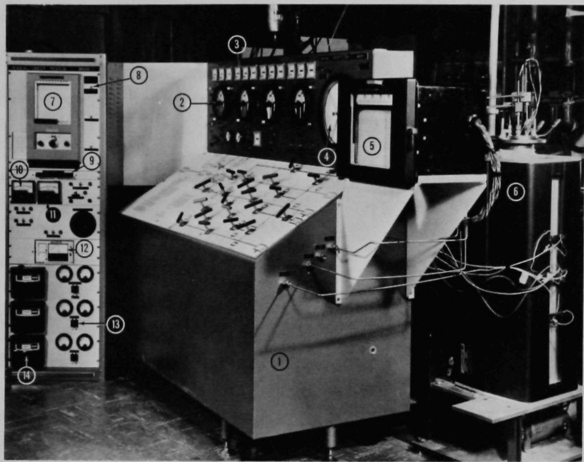
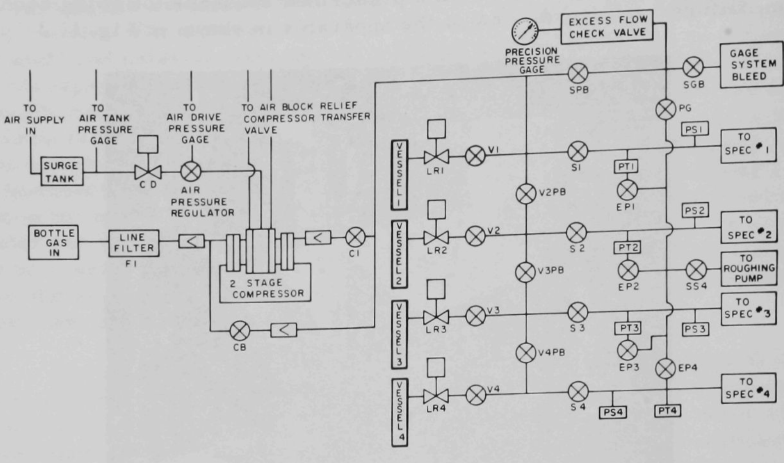


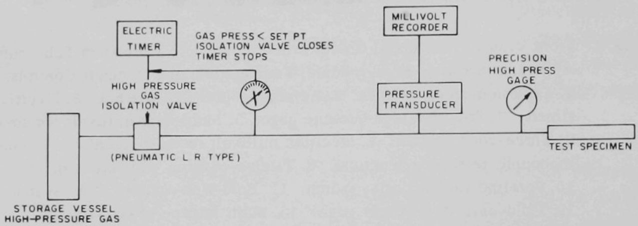
Fig. 1. Front View of the Biaxial Creep, Stress-rupture, and Short-term Tube-burst Apparatus Showing High-pressure, Temperature, and Vacuum Controls. 1. Explosion-proof cabinet. 2. Adjustable pressure switches. 3. Electric timers. 4. Precision high-pressure gage. 5. Multipoint millivolt recorder. 6. Three-zone furnace. 7. Precision millivolt recorder (AZAR). 8. Thermocouple reference junctions. 9. Twelve-position pushbutton switch. 10. Foreline vacuum relay switch. 11. Hold-line vacuum relay switch. 12. Cold-cathode vacuum gage. 13. Main furnace power switches. 14. Digital-type proportional temperature controllers. ANL Neg. No. 306-271A.

A. High-pressure Gas System

The high-pressure gas system is completely contained within a heavy-gage, explosion-proof cabinet to protect the operator. The high-pressure piping arrangement is shown in Fig. 2a. It consists of four separate high-pressure systems, each with a high-pressure gas storage vessel, a pneumatically operated high-pressure isolation valve (LR-type), a pressure transducer (PT), a pressure switch (PS), and several hand valves. The high-pressure piping arrangement provides several special features that can be implemented by opening or closing hand valves. With hand valves V2PB, V3PB, and V4PB closed, the four high-pressure gas systems can be operated as separate units, each at a different pressure. With the same hand valves open, the adjacent high-pressure gas systems can be operated in parallel. Hand-valve manipulations also provide for high-pressure gas bleed-off from any of the four high-pressure gas systems, and for evacuation of all test specimens before the start of a biaxial creep test.



(a)



(b)

Fig. 2. High-pressure Section in Biaxial Creep, Stress-rupture, and Short-term Tube-burst Apparatus. (a) Compressor and overall high-pressure piping. (b) One of four separate high-pressure gas systems in the apparatus. Neg. Nos. MSD-53231 and MSD-53233.

The pressure bleed-off capability is used to adjust gas pressure between the storage vessels in the individual gas systems and to depressurize specimens for diameter measurements. Evacuation and purging of specimens before the start of a test run are especially important for refractory metals. The creep properties of these materials can be changed appreciably by part-per-million quantities of such interstitial contaminants as oxygen, nitrogen, and carbon.[9] The diaphragm compressor is the principal provision against specimen contamination by hydrocarbons.

The 12-in.-dia precision pressure gage shown in Figs. 1 and 2a can be placed in any of the four high-pressure systems by the operation of hand valves EP1, EP2, EP3, and EP4. This gage serves as a secondary pressure standard for checking the pressure transducers and as an auxiliary pressure-indicating device in the event of a pressure-transducer malfunction.

The four high-pressure systems are serviced by the same air-driven, two-stage diaphragm compressor. Each gas-storage vessel is pressurized individually with bottled argon or helium gas at pressures to 30,000 psig. The compressor is bypassed for gas pressures up to 2200 psig, in which case the vessels are pressurized directly from the commercial-gas bottle. Hand valves C1 and CB are used to isolate the high-pressure systems from the compressor and the commercial-gas bottle. Check valves located on either side of the compressor and in the bypass line provide a safeguard against accidental overpressurization of the commercial-gas container as a result of bleed-back of gas from any of the storage vessels.

B. Vacuum Furnace

The complete vacuum system is shown schematically in Fig. 3a. Both the furnace chamber and the primary vacuum piping are constructed of 4-in., Schedule-40 pipe to promote rapid pumpdown of the system following specimen failure. The furnace chamber is Inconel 600, and the primary piping is Type 304 stainless steel. The vacuum pumping system is constructed of conventional components that include a 6-in. oil-diffusion pump, a 25-cfm mechanical roughing pump, and a 15-cfm mechanical holding pump. Backstreaming of diffusion pump oil toward the furnace chamber is minimized by the water-cooled "cold cap" in the diffusion pump and the water-cooled "chevron" baffle located at the inlet to the diffusion pump.

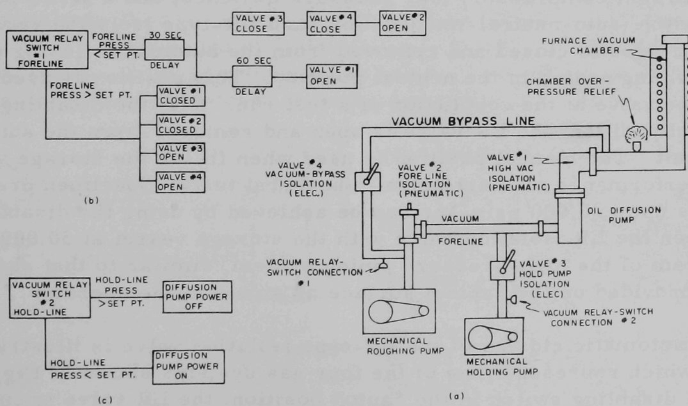


Fig. 3. Vacuum Section in Biaxial Creep, Stress-rupture, and Short-term Tube-burst Apparatus. (a) Furnace vacuum chamber, primary vacuum piping, and vacuum pumping system. (b) Foreline vacuum controls. (c) Hold-line vacuum controls. Neg. No. MSD-53235.

Following specimen failure, the initial pumpdown of the furnace chamber is accomplished through the vacuum bypass line. At a preset pumpdown pressure, the furnace chamber is automatically placed on the primary pumping line. The sequential operation of the vacuum valves in Fig. 3a is described in detail in Sec. C below. A pressure-relief valve is provided on the primary vacuum line as a safeguard against accidental overpressurization of the furnace chamber. This could occur by a malfunction of the LR-type isolation valve following specimen failure, in which case the high-pressure gas in the storage vessel would flood the furnace chamber. The relief valve safely dissipates this gas at a furnace-chamber pressure of 15 psig.

The furnace chamber is heated in a 5-in.-dia by 37-in.-long, three-zone, electric tube furnace. Each zone is powered by a silicon-controlled rectifier with current-limiting provisions. The furnace temperature is controlled by a digital-type proportioning controller. The 12-in.-long uniform temperature zone has a range of 100-1200°C and can be maintained within ±2°C. The furnace chamber can be operated at a vacuum of about 1×10^{-5} mm Hg or at a positive inert-gas pressure of 15 psig. A cold cathode-ion gage is used to measure furnace-chamber vacuum. A stainless steel "cross" divides the furnace chamber into four equal quadrants and provides isolation between specimen bundles. This precaution is taken to minimize intraquadrant influences in the event of violent specimen rupture.

C. Pressure, Vacuum, and Temperature Controls

All the automatic high-pressure controls are located on the vertical panel of the equipment shown in Fig. 1. They include the operating controls for the diaphragm compressor, four pressure switches, and a three-position disabling switch (auto-neutral-manual) for each LR-type isolation valve. The LR-type valve is closed and removed from the automatic closing circuit with the disabling switch in the neutral position. This position is used to deactivate the valve at the conclusion of a test run. With the disabling switch in the manual position, the LR valve is open and removed from the automatic closing circuit. The manual position is used when filling the storage vessels and in the performance of short-term, tube-burst tests. Specimen pressurization rates up to 20,000 psig/sec can be achieved by using the disabling switch to open the LR isolation valve with the storage vessel at 30,000 psig. A line diagram of the high-pressure piping system, similar to that shown in Fig. 2a, is provided on the cabinet surface as an aid to the operator.

The automatic closing of the LR-type isolation valve is illustrated in Fig. 2b, which represents one of the four gas systems shown in Fig. 2a. With the LR disabling switch in the "auto" position, the LR valve is open and the specimen is pressurized from the storage vessel. System pressure is monitored by the pressure transducer and is indicated on a millivolt recorder. This pressure can also be visually indicated on the precision pressure gage. The adjustable electrical contact on the pressure switch is set arbitrarily close to the pressure-indicator needle, and the electric timer is started at the initiation of a test run. When specimen failure occurs, the pressure drop in the system closes the electrical contact of the pressure switch, which, in turn, simultaneously stops the electric timer and closes the LR isolation valve. A record of the system depressurization is obtained on the millivolt recorder, and the test on that system is terminated.

Two thermocouple vacuum gages are used as automatic vacuum controls. Each is equipped with an electronic relay and an adjustable set point. One gage controls the operation of the four valves in the vacuum system shown in Fig. 3a by sensing the foreline pressure. The other vacuum gage senses the pressure in the hold line and controls power to the diffusion pump. The operation of the vacuum controls is described by referring to Figs. 3b and 3c.

Under normal operating conditions, valves 1 and 2 are open and valves 3 and 4 are closed. When the foreline pressure exceeds the set-point value (~100-200 μ Hg) following a specimen failure, the electronic relay initiates a valve-sequencing operation. Pneumatic valves 1 and 2 close, and the electrically driven valves 3 and 4 open, in that order. This places the roughing pump on the furnace chamber through the vacuum bypass line for rapid pumpdown. When the furnace chamber pressure is decreased below the set-point value, the valve sequence is reversed. Thirty seconds after the pressure is reduced below the set-point value, valves 3 and 4 close and valve 2 opens, in that order. The closing of valve 4 initiates the closing of valve 3, which, on closing, initiates the opening of valve 2. After another 30-sec delay, valve 1 opens, and the test is continued under high vacuum on the remaining tube specimens. The above valve sequence occurs after each specimen failure. During the time when valves 1 and 2 are closed and 3 and 4 are open, the diffusion pump is blanked off and backed up by the holding pump. If the pressure in the holding line should increase above the set-point value of the second thermocouple gage, the power to the diffusion pump is automatically cut off to prevent oxidation of the diffusion pump oil.

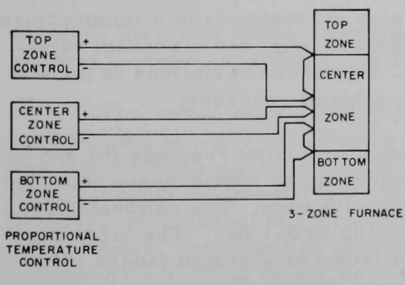


Fig. 4. Differential Thermocouple Arrangement for Temperature Control in the Three-zone Furnace. Neg. No. MSD-53234.

Furnace temperature is controlled by three digital-type proportioning controllers using Chromel-Alumel thermocouples. The control thermocouples are wired in a differential manner, as shown in Fig. 4. The controller for the center zone of the furnace is the "master," and the controllers for the top and bottom zones are "slaves." With this arrangement, the power to the top and bottom zones follows the setting of the master controller to maintain a predetermined temperature differential between zones. This temperature differential can be made as small as desired. Furnace-temperature control is within ±4°C below 400°C and ±2°C above 400°C.

The pressure, temperature, and vacuum controls interact through electric relays located at the right-hand end of the explosion-proof cabinet.

III. DATA READOUT INSTRUMENTATION

Test parameters that are either monitored or recorded include the outside furnace temperatures, specimen temperatures, furnace vacuum, gas pressure in each high-pressure system, and the duration of the test. Both the furnace and specimen temperatures are monitored at the top, middle, and bottom of the center zone. Conventional Chromel-Alumel thermocouples are used to measure all temperatures. Specimen pressures are monitored by elastic cavity pressure transducers, and the duration of each test is indicated by a digital electric timer. All sensors (pressure, temperature, and vacuum) have an electromotive force (emf) output between 0 and 50 mV over their useful range; therefore, the output from all sensors can be indicated on a single recorder.

Two recorders are provided for monitoring and/or recording the emf output from each sensor. One is a conventional 12-point instrument with a fixed 0-50-mV range (0.5 mV per chart division), and the other is a precision adjustable-zero, adjustable-range (AZAR) instrument with a 0-100- or 0-1-mV range (0.01 mV per chart division). Both instruments are uncompensated.

The multipoint recorder is used primarily to monitor the status of a long-term test by observing the periodic variations of the sensor emf's as a function of time. Since the instrument is uncompensated, the temperature readings are referred to the ambient temperature and are therefore influenced by the normal variations in the ambient temperature. The millivolt equivalent of the smallest chart division corresponds to a temperature variation of 12.5°C, a pressure variation of 250 psig, and a vacuum variation of about 1×10^{-2} mm Hg. Therefore, only gross variations in the test parameters are easily observed on the multipoint recorder.

The AZAR recorder is used to obtain precision readings for any of the sensor outputs. A selected sensor output can be continuously recorded to determine the magnitude of its variation with time. The calibrated span can be arbitrarily set at any value from 0-100 to 0-1 mV. The incoming signal can also be suppressed (subtracted from) or elevated (added to) by 50 mV. Therefore, in recording temperature from a thermocouple output, it is possible to suppress up to 50 mV and read the remaining tenths of millivolts on a 1-mV calibrated scale. Under these conditions, the smallest chart division corresponds to a temperature variation of 1/4°C.

Each of the sensor outputs that are continuously displayed on the multipoint recorder is easily transferred to the AZAR recorder by pressing the appropriately numbered pushbutton located just below the AZAR. The emf outputs of the three specimen thermocouples are connected to the AZAR recorder through a millivolt reference junction. The reference junction gives an output that is the millivolt equivalent of 0°C for a Chromel-Alumel thermocouple.

IV. SPECIMEN DESIGN AND PREPARATION

The standard specimen design for unirradiated materials is shown in Fig. 5. The 4-in. length is at least 10 times the diameter to minimize the influence of the welded ends on the biaxial creep behavior. Approximately 90-95% of the specimen volume is displaced with a solid rod of the same material as that of the specimen. This reduces the volume of high-pressure gas within the specimen at failure and minimizes specimen tearing after failure. The top and bottom end plugs are tungsten-inert-gas (TIG) welded.

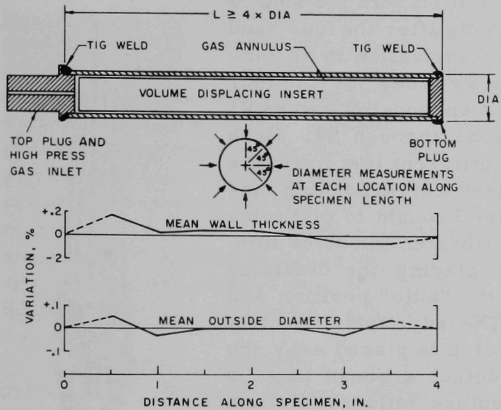


Fig. 5. Tubular Specimen Design Showing Typical Variations in Outside Diameter and Wall Thickness of Thin-wall Tubing Considered as Potential Fuel Cladding. Neg. No. MSD-53232.

Unirradiated test specimens are usually made from commercial tubing intended for cladding applications in fuel alloy irradiations or for in-reactor unfueled biaxial creep experiments.[7] The material is therefore given a thorough nondestructive test inspection by eddy-current techniques to ensure material quality.

The initial inside and outside diametral inspection of the 4-in. specimen lengths is made to ±0.00005 in. with precision air gages. These values are recorded for each 1/2-in. interval along the specimen length. Tube-wall thickness is calculated from these values. The diametral strain at each 1/2-in. interval is calculated using the original outside-diameter values. Typical variations in the outside diameter are <±0.1%. Wall-thickness variations are about +0.2%, as shown in Fig. 5. Diametral ovality along the specimen length is also <0.1%. A completed standard specimen is shown in Fig. 6.

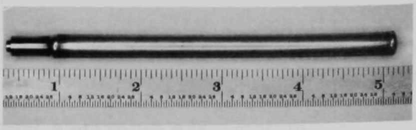


Fig. 6

Standard-length Tube Specimen Used to Determine Creep-Strain-profile Behavior of Potential Nuclear Fuel-cladding Materials at Elevated Temperatures. Neg. No. MSD-53327.

V. BIAXIAL CREEP-TEST PROCEDURE

Figure 7 shows one of four specimen bundles used in a single creep test. Each specimen bundle is individually connected to a high-pressure gas source through bulkhead fittings located at the right end of the high-pressure cabinet. With hand valves SSV, EP1, EP2, EP3, and EP4 open, the four specimen bundles are evacuated with a small mechanical pump provided for this purpose. The specimens are backfilled with the source gas to a pressure of about 20-50 psig after the four hand valves are closed. Specimen pressurization is accomplished by placing the disabling switches for the four LR-type valves in the manual position, opening valves V1 through V4, and cracking valves S1 through S4. Each specimen bundle is brought to a different test pressure that is selected to yield the desired corresponding tangential stress. The specimens are brought to test temperature in about 3-4 hr and equilibrated for 30-60 min. The creep test is initiated by placing the disabling switches for the LR valves in the "auto" position and starting the digital counters. The adjustable electrical contact on each pressure switch is placed near the pressure-indicator needle to detect a gross loss in specimen pressure following rupture failure. Helium gas is preferred as the pressurizing medium because it also serves as a built-in leak-detection capability. The small atomic diameter of helium permits the detection of very small pinhole-leak failures.

The biaxial creep test is interrupted at selected intervals with a 24-hr timer for diametral measurements. These interruptions are scheduled to allow about 3-4 hr for cooling before the start of the workday. Diametral measurements are made to the nearest ±0.0001 in. with a comparator micrometer at room

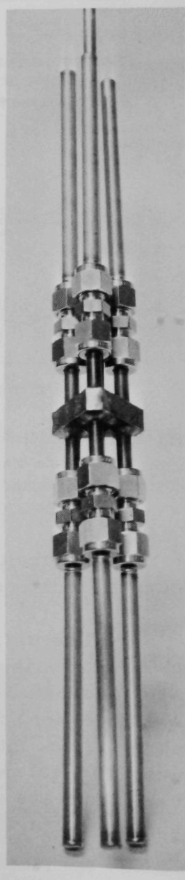


Fig. 7

Arrangement of Tube Specimens in a Six-specimen Bundle for Creep Testing at Elevated Temperatures under Biaxial Load. Neg. No. MSD-52321.

temperature after specimen depressurization. Four measurements are made at each 1/2-in. interval along the specimen length (see Fig. 5), and the average value is used to determine the diametral strain $\Delta D/D_0$. These diametral-strain values are plotted as a function of time, and the resultant curve is used as a guide to determine an appropriate time interval between successive interruptions. Strain measurements are made at more frequent intervals during the primary and tertiary stages of biaxial creep and less frequently during the secondary or steady-state stage.

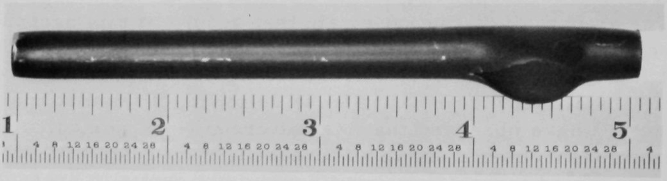
On resumption of the test, specimens are pressurized to about 50-60% of the test pressure during heating. This procedure retains the microstructure corresponding to the accrued strain history before shutdown. The amount of diametral strain that occurs at this pressure during the 3-4-hr heating period is small compared with that during hundreds of hours at full test pressure. However, during heating, this reduced internal pressure is sufficient to prevent stress relieving of the material. Conway and Flagella[10] have observed that biaxial creep tests, periodically interrupted for strain measurements, exhibit decreased creep resistance when compared with uninterrupted tests. However, they did not partially pressurize the specimens during heating that followed a test interruption, and therefore stress relieving could have occurred, which would account for their observation. It has been our observation that, for periods up to 500 hr, a specimen interrupted every 100 hr will show no greater difference in diametral strain than the differences usually found between identical specimens tested under the same conditions of temperature and stress. In the latter case, the diametral-strain differences are considerably less than 10%.

Biaxial creep tests can be conducted under constant-load (constant-pressure) or constant-stress (decreasing-pressure) conditions. Under constant-pressure conditions, the specimens are connected to the gas source during the test. Since the volume of the storage vessel is large compared with the total specimen volume, the specimens in each bundle can strain to failure without altering their internal pressure. Under this mode of operation, the tangential stress increases with diametral strain because of an accompanying decrease in wall thickness. The relationship between the tangential stress (σ_t) and the diametral strain ($\Delta D/D_0$) is illustrated in the appendix. The same would be true in a uniaxial creep test conducted under constant load.

Under decreasing pressure conditions, the specimens are isolated from the gas source after pressurization at temperature. With this mode of operation, the specimen pressure will decrease as the specimen volume increases. The rate of pressure decrease will depend upon the change in the ratio of the increase in specimen volume to the initial volume. This relationship is given in the appendix as the tangential stress versus diametral strain for various percentages of specimen-volume displacement. Thus, the value of σ_t decreases only slightly at diametral strains up to 25% with zero specimen-volume displacement. On the other hand, the drop in σ_t is very large even at low values of diametral strain with 90% specimen-volume displacement. With zero specimen-volume displacement, the slight drop in specimen pressure due to diametral strain is accompanied by a decrease in wall thickness to maintain σ_t almost constant.

VI. TEST RESULTS AND DISCUSSION

The three types of specimen failures observed in biaxial creep tests under gas-pressure loading are shown in Fig. 8. They are, from top to



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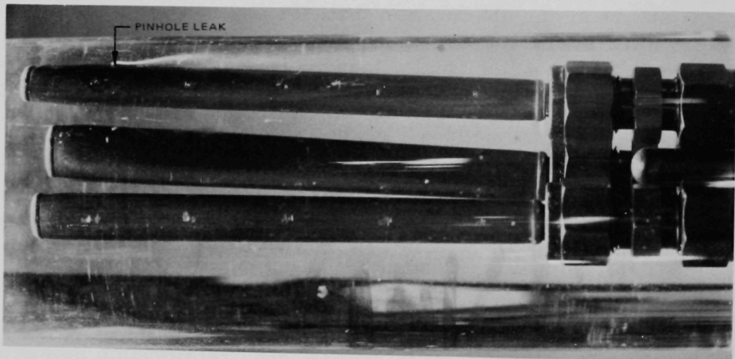
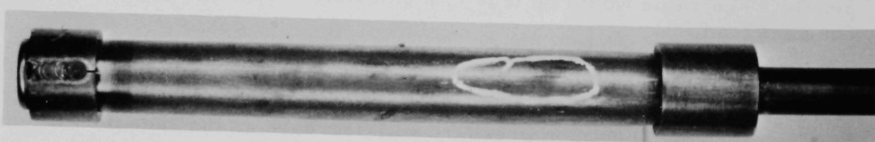


(b) 1X



(c) 1.4X

Fig. 8. Failure Profiles of Austenitic Tube Specimens Biaxially Creep Tested at 650°C. (a) Transgranular plastic instability failure $\dot{\varepsilon}_m = 1.4 \times 10^{-2}\ hr^{-1}$ (Type 304L stainless steel). (b) Intergranular pinhole-leak failure $\dot{\varepsilon}_m = 4.2 \times 10^{-4}\ hr^{-1}$ (Type 304L stainless steel). (c) Intergranular fissure failure $\dot{\varepsilon}_m = 7.5 \times 10^{-5}\ hr^{-1}$ (Type 304 stainless steel). Neg. Nos. MSD-53334, MSD-52397, and MSD-43975.

bottom, catastrophic rupture, pinhole leak, and fissure. Failure by catastrophic rupture results in a gross and sudden loss in specimen pressure. It is detected by the closing of the electrical contact on the pressure switch. In contrast, the small pinhole leak usually results in a degradation of the furnace vacuum and is detected by an increase in the foreline pressure. The fissure failure may be detected either by a loss in specimen pressure or a rise in foreline pressure, depending on its size and the resultant gas-leak rate from the specimen. Each specimen failure shown in Fig. 8 has a characteristic strain profile, as illustrated in Fig. 9. The strain profile for specimens that fail by catastrophic rupture are usually characterized by an overall high level of diametral strain and a localized area of high diametral strain at the rupture. Pinhole failures have a lower overall level of diametral strain and a localized area of diametral strain much lower than that for the rupture. Fissure failures have the lowest overall level of diametral strain and usually no areas of localized strain.

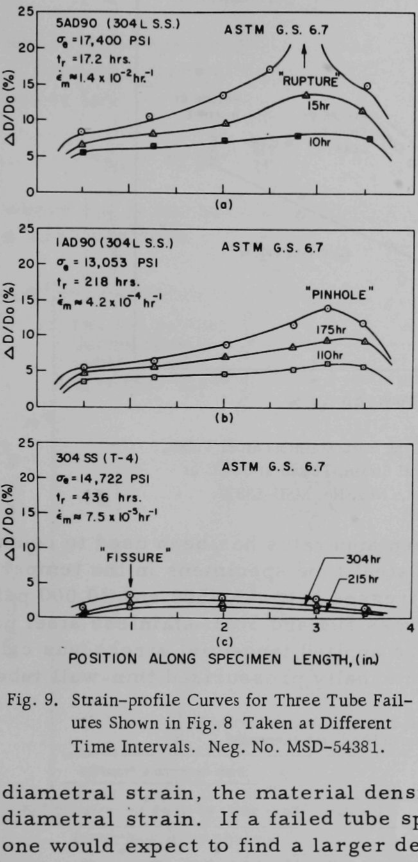


Fig. 9. Strain-profile Curves for Three Tube Failures Shown in Fig. 8 Taken at Different Time Intervals. Neg. No. MSD-54381.

The fact that the diametral strain profile in biaxial creep testing varies along the specimen length can be effectively used in the study of the mechanisms of cladding failure. Since wall thinning increases directly with diametral strain, the material density should also decrease directly with diametral strain. If a failed tube specimen is sectioned along its length, one would expect to find a larger density decrease $(-\Delta\rho/\rho_0)$ at locations of high diametral strain and a small density decrease at locations of low diametral strain. Furthermore, the change in material density at a given diametral strain might be expected to vary with the rate of plastic deformation, because of differences in failure mechanisms at high and low strain rates.[11,12] The variation in material density as a function of diametral strain at high ($\dot{\epsilon}_m = 0.4\text{-}1.4 \times 10^{-2}$ hr^{-1}) and low ($\dot{\epsilon}_m = 1.8\text{-}4.2 \times 10^{-4}$ hr^{-1}) strain rates is illustrated in Fig. 10 for Type 304L stainless steel tested at 650°C. In a systematic study of cladding failure, the six specimens in each bundle would be duplicates. Because the biaxial creep test for each bundle is automatically terminated at the first specimen failure, the remaining unfailed specimens would provide a range of diametral strains up to failure. Furthermore, a single test could provide such failure samples at four strain rates, since each specimen bundle could be tested at a different internal pressure.

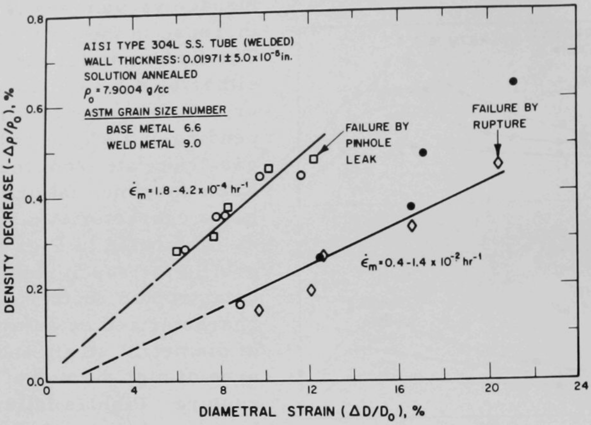


Fig. 10. Variation in Density of Type 304L Stainless Steel Tubes, as a Function of Diametral Strain, Tested at 650°C at High and Low Strain Rates. Neg. No. MSD-53377.

The semiautomatic biaxial creep apparatus has been used to conduct tests on thin-wall austenitic stainless steel tube specimens in the temperature range 550-700°C and at applied stresses between 7500 and 40,000 psi. Results of chemical analyses of the Types 304 and 304L stainless steel used in these tests are given in Table I. The applied tangential stress was calculated using the Lemé formula for an internally pressurized thin-wall tube.[13]

TABLE I. Compositions and Room-temperature Mechanical Properties of Thin-wall Austenitic Stainless Steel Tubes Used in Biaxial Creep Experiments[a]

Material	Contents, %										Room-temperature Properties			
	C	Mn	P	S	Si	Ni	Cr	Ti	Cu	Mo	UTS, ksi	YS, ksi	Elong., %	Hardness, Rb
	Vendor's Analysis													
Type 304L Stainless Steel[b] (annealed)	0.30	1.37	0.01	0.007	0.62	9.26	18.29	0.02	0.074	0.02	81	36.5	58	60
													55	64
	Confirming Analysis--Commercial													
	0.30	1.30	0.012	0.013	0.61	8.16	18.47	-	-	-	-	-	-	-
	Vendor's Analysis													
Type 304 Stainless Steel[c] (annealed)	0.06	1.66	0.029	0.019	0.43	9.71	18.51	-	-	-	90	38	61	60
													62	64
												Interstitials, ppm		
	Confirming Analysis--ANL											O	N	H
	0.061	-	-	-	-	9.16	18.44	-	-	-		291	788	4.5

[a]All tubes 0.290-in. OD by 0.250-in. ID by 0.20-in. nominal wall thickness; completely inspected by ultrasonic and eddy-current techniques.
[b]Heat 840505; welded tube.
[c]Heat 71059; seamless tube.

The Von Mises yield criterion is assumed to apply during plastic deformation. The effective stress (σ_e) that causes the plastic deformation is calculated by

$$\sigma_e = 0.866\sigma_a, \quad (1)$$

where σ_e is the effective stress, and σ_a is the applied tangential stress. It is further assumed that plastic flow during steady-state creep obeys the power law

$$\dot{\epsilon}_m = B\sigma_e^n, \quad (2)$$

where $\dot{\epsilon}_m$ is the minimum or steady-state diametral creep rate, and B and n are constants.

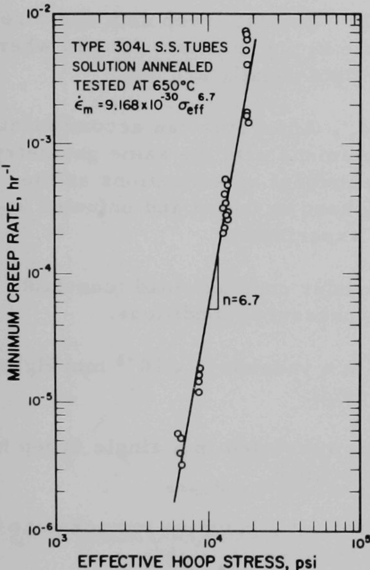


Fig. 11. Minimum Creep Rate vs Effective Stress for Solution-treated Type 304L Stainless Steel Biaxially Creep Tested at 650°C. Neg. No. MSD-53007.

Biaxial creep data for Type 304L stainless steel tubes tested at 650°C and at stresses between 7500 and 20,000 psi are plotted in Fig. 11 as the minimum creep rate ($\dot{\epsilon}_m$) versus effective stress (σ_e). A least-squares analysis of these data yields the following values for the constants in Eq. 2: $B = 9.16 \times 10^{-30}$ and $n = 6.7$. The stress dependence of the minimum creep rate (n) for Types 304 and 304L austenitic stainless steel in this temperature and stress range is generally taken as 6 to 7. Additional biaxial creep data for Types 304 and 304L stainless steel tubes tested in the temperature range 550-700°C and at stresses between 7500 and 40,000 psi are plotted in Fig. 12. The temperature-compensated Zener-Hollomon parameter is used because many of the tests conducted at the different temperatures were also conducted at different applied stresses. In plotting Fig. 12, an activation energy of 95,000 cal/mole was assumed, since this value is generally accepted as an average value for austenitic stainless steel. A least-squares analysis of the data in Fig. 12 yields a stress dependence of 6.8. Since this value of the constant n in Eq. 2 is close to that determined from Fig. 11, the assumed value of 95,000 cal/mole for the activation energy is confirmed.

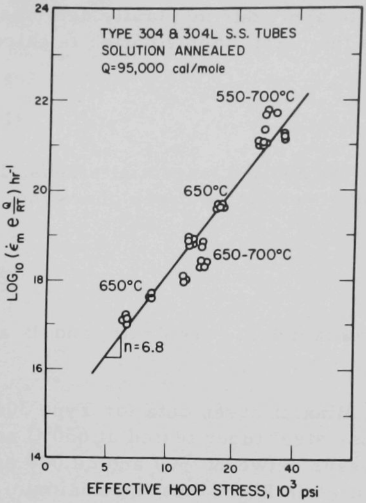


Fig. 12

Zener-Hollomon Temperature-compensated Parameter vs Effective Stress of Solution-annealed Types 304 and 304L Stainless Steel Pressurized Tubes. Neg. No. MSD-53008.

VII. SUMMARY

The biaxial creep apparatus provides a method of conducting long-term creep tests on tube specimens at temperatures and stresses closely approximating in-reactor applications. Since the pressure integrity of this apparatus is equal to that of an actual fuel element, the long-term specimen response to such factors as temperature, stress, and mechanical defects will be similar to that of the fuel cladding under comparable service conditions. The advantages of biaxial creep tests are as follows:

1. Biaxial creep data are directly applicable to fuel-element design, whereas uniaxial data usually are not.

2. Apparatus can accommodate tube specimens with the same geometry and dimensional specifications as the cladding used in fueled and unfueled in-reactor experiments.

3. Creep tests can be conducted under constant-load (constant-pressure) or constant-stress (decreasing-pressure) conditions.

4. Creep tests can be conducted in a vacuum (1×10^{-5} mm Hg) or an inert-gas environment (pressure = 15 psig).

5. Up to 24 specimens can be accommodated in a single creep test, which greatly reduces the test time per specimen.

6. A single test can yield creep data at a common temperature and four stresses for as many as six materials.

7. The test is automatically terminated for failed specimens, but continued for the remaining specimens.

8. Pinhole failures less than 0.0001 in. in diameter are easily detected.

9. Tube specimens are produced that are ideal for fuel-cladding fracture studies.

10. Apparatus can be used to proof-test fabricated tubing.

APPENDIX

Fractional Tangential Stress as a Function of Diametral Strain for Constant- and Decreasing-load Conditions

Figures 13 and 14 illustrate the change in the applied tangential stress as a function of diametral strain for tube specimens tested under constant- and decreasing-load conditions, respectively. Constant volume and uniform plastic deformation of the material are assumed to be valid to 25% diametral strain. The latter assumption is not always true for thin-wall tubes, inasmuch as nonuniform wall thinning has been observed at moderate diametral strains.[4]

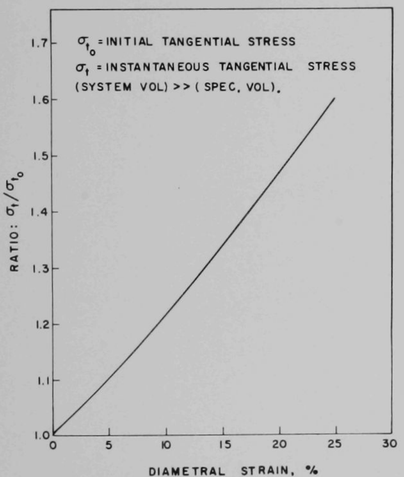


Fig. 13. Increase in Applied Tangential Stress with Diametral Strain for Tube Specimens Tested under Constant Load (internal pressure). Neg. No. MSD-53558.

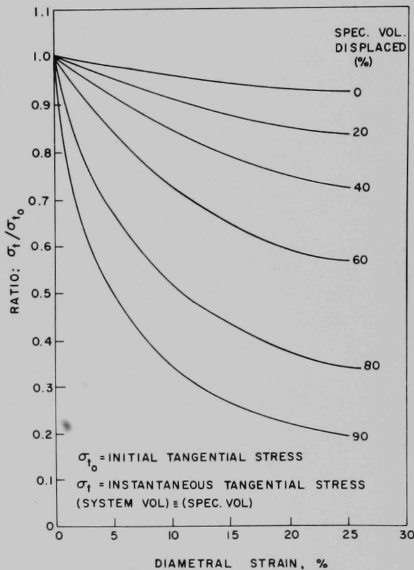


Fig. 14. Decrease in Applied Tangential Stress with Diametral Strain for Internally Pressurized and Sealed Tube Specimens. Neg. No. MSD-53480.

Under constant-load conditions, the system volume is large compared with the specimen volume. Therefore, the internal specimen pressure remains constant up to specimen failure. This is true whether specimen volume is or is not partially displaced with a solid rod insert. The increase in tangential stress with an increase in diametral strain is the result of specimen-wall thinning.

Under decreasing-load conditions, the system volume is identical to the specimen volume. The decrease in tangential stress is the product of the increase in specimen volume and the accompanying decrease in wall thickness due to plastic strain. The drop in tangential stress per unit of diametral strain is greatest in those specimens that have the smallest initial volume (largest volume displacement with a solid insert).

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